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Review

Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory

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Abstract

Use of subsurface drip irrigation (SDI) has progressed from being a novelty employed by researchers to an accepted method of irrigation of both perennial and annual crops. This paper reviews the SDI research conducted by scientists at the Water Management Research Laboratory over a period of 15 years. Data are presented for irrigation and fertilization management on tomato, cotton, sweet corn, alfalfa, and cantaloupe for both plot and field applications. Results from these studies demonstrated significant yield and water use efficiency increases in all crops. Use of high frequency irrigation resulted in reduced deep percolation and increased use of water from shallow ground water when crops were grown in high water table areas. Uniformity studies demonstrated that after 9 years of operation SDI uniformity was as good as at the time of installation if management procedures were followed to prevent root intrusion. Published by Elsevier Science B.V.

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1. Introduction

Microirrigation has developed rapidly since the early 1960s with the advent of the modern plastics industry. In the United States from 1981 to 1995 the area irrigated by microirrigation has increased from 185,000 ha to over 1,000,000 ha which represents 5% of the total irrigated area. There are approximately 626,000 ha of microirrigation in California with roughly 99,000 ha of the total being in subsurface drip irrigation (SDI). Based on current trends of adoption there should be a total of 3 million ha of microirrigated land in the world by the year 2000 representing only 2% of the total irrigated land in the world.

Some advantages of microirrigation include improved water and nutrient management, potential for improved yields and crop quality, greater control on applied water resulting in less water and nutrient loss through deep percolation, and reduced total water requirements. Phene et al. (1987) demonstrated significant yield increases in tomatoes with the use of high frequency SDI and precise fertility management. In a recent study Hutmacher et al. (1996) demonstrated yield increases in alfalfa production using SDI systems buried at depths of 0.7 m. Cotton yields have also been improved using SDI (Smith et al., 1991; Ayars et al., 1998). Water use efficiency has been significantly improved through the use of SDI (Phene et al., 1986b).

Most microirrigation has been on permanent plantings such as trees and vines with applications to field crops being limited. Application of microirrigation technology to field crops is difficult because of the potential for surface-installed drip tubing interfering with cultural operations. To alleviate this difficulty, the use of SDI has been proposed and tested. The design of the SDI system is the same as for surface systems except the tubing is buried. Burying the tubing adds additional initial cost to the system but eliminates the need to install and remove tubing at the beginning and end of each growing season. Root intrusion, distribution uniformity, tubing damage from equipment and burrowing animals are all concerns with the operation of a SDI system, since the system is no longer in view. If the advantages of microirrigation can be realized with a subsurface system and the concerns be alleviated, there is tremendous potential for the adoption of this technology on field crops as well as on permanent plantings.

The objectives of this paper are to review the 15 years of research by scientists at the Water Management Research Laboratory related to application of SDI in production of field crops, to summarize the results, and to identify the successes, the limitations, and the areas requiring further research.

2. Plot studies

Plot studies were conducted at two locations in the San Joaquin Valley (SJV) and one location in the Imperial Valley of California. The SJV studies were on the research farm at California State University, Fresno (CSUF) and at the University of California West Side Research and Extension Center, formerly the West Side Field Station (WSFS) and the Imperial Valley studies were done at the USDA-ARS Irrigated Desert Research Station in Brawley, CA. The following discussion is divided into the procedures and results at the CSUF location, the procedures and results at the WSFS and the studies at the Imperial Valley location.

2.1. California State University, Fresno

2.1.1. Materials and methods

In 1981, a SDI system was installed in a replicated-plot experiment on the California State University, Fresno (CSUF) farm in Fresno, CA. The irrigation tubing (Agrifim, in-line emitters 2 Lph, spaced 61 cm) was shanked in at a depth of 0.46 and 1.52 m apart in 1.52 m beds which were shaped before planting. The soil is a Handford sandy loam (Typic Xerorthents Entisols). Tomato seeds (*Lycopersion esculentum* Mill, UC82B) were planted on day of year (DOY) 97 with a precision planter at a rate of 173,000 seeds per ha and were germinated by sprinkler irrigation.

Irrigation control was performed semi-automatically with a commercial irrigation controller (Motorola, Matarol 2000)[2]. Daily evaporation was measured directly with an open evaporation pan and calculated indirectly using van Bavel's evapotranspiration (E_t) model with a Z_o coefficient of 1.5. A crop coefficient proportional to the canopy spread was used to adjust the E_t values obtained with the pan and van Bavel's model. A computerized on-site weather station was used to collect the hourly climatic data needed for the E_t calculations. Irrigation control was also performed automatically with electronic soil moisture sensors and a computerized data acquisition system (Phene et al., 1986b).

Fertilization consisted of a pre-plant broadcast application of 89.6 kg ha^{-1} of nitrogen followed by post-emergence daily application of urea-sulfur fertilizer through the trickle irrigation system totaling 86.1 kg ha^{-1}. The plots of the furrow-irrigated treatment were side dressed with 101 kg ha^{-1} of N on 12 May 1981. Water applied, petiole N, P, K, and plant height and spread were measured weekly.

The experiment consisted of eight treatments replicated three times. The plot size of each replication was 92.9 m^2 consisting of five 1.52 m wide beds, 12.2 m long. Plots in Treatment 1 (furrow irrigation) were first irrigated on 14 May 1981. After the sixth true leaf stage (May 27) differential irrigation began in plots in the seven subsurface drip irrigation (SDI) treatments. Treatments 2, 3, and 4 were based on three daily E_t rates measured with open, screened, and 75% of the open class A evaporation pans, respectively; Treatment 5 was based on potential E_t calculated by van Bavel's equation. Irrigation of plots in Treatments 6, 7 and 8 was initially based on soil moisture potential of 15, 25, and 35 kPa, respectively, and as the season progressed, the soil moisture threshold potentials for irrigation of Treatments 6, 7, and 8 were altered to more closely meet plant soil water potential requirements by subsequently changing the soil moisture thresholds to 20, 30, and 40 kPa first, then to 25, 35, and 45 kPa, and finally to 35, 45 and 55 kPa, respectively.

[2] Equipment names are provided for the benefit of the reader and do not imply endorsement by USDA-ARS

2.1.2. Results

The total water applied, marketable yields, soluble solids and water use efficiency are summarized in Table 1. Marketable tomato yields are shown in Table 1 and in all cases, the SDI plots produced more marketable tomatoes than the furrow-irrigated tomatoes. Since the furrows were short and dammed at both ends, all water applied with furrow irrigation infiltrated the plots and water was distributed uniformly along the beds, probably at a relatively high application uniformity; hence the differences in growth and yield must have resulted somewhat from the irrigation method and/or frequency.

Tomato quality was evaluated at harvest; fruit weight, alcohol insoluble solids, color, and citric acid content were not affected by the irrigation methods or control treatments. Table 1 shows that total soluble solids were significantly higher in Treatments 2 and 8 and significantly lower in Treatments 1 and 5; similarly, total solids were low in Treatments 1 and 3 when compared to Treatment 8, but were not significantly different from all other treatments. Specific gravity was only randomly affected.

Irrigation frequency varied with the treatments. Treatment 1 (furrow) was irrigated approximately once every 6 days during peak E_t periods, while Treatment 4 was irrigated twice per day during the same period. Treatment 5 was irrigated 4 to 6 times a day while Treatment 6 was irrigated 6 times a day. Treatments 7 and 8 were irrigated multiple times per day but less than 6. Treatments 2 and 3 were irrigated at a frequency between once every six days and twice per day. The average irrigation requirement of tomatoes in the SJV is approximately 750–875 mm per year. With the exception of Treatments 4, 6 and 8 the remaining treatments received approximately this amount of water.

The average marketable yield of tomato in California is approximately 78 Mg ha^{-1} which is exceeded in all treatments. The data show that yields were significantly better with the SDI than the furrow. This might have been a result of the frequency or soil water limitations created by the soil, i.e. poor infiltration in the furrow plots. Use of SDI eliminated the effect of surface sealing which occurred in the furrow irrigated plots during the irrigation season. The studies were moved from the CSUF site to the WSFS site because tomatoes are not generally grown on the soil type located on CSUF.

2.2. West side field station

2.2.1. Materials and methods

At the University of California West Side Field Station a progression of experiments using the SDI system evaluated first the water management and then the combined management of water and fertilizer on processing tomatoes, sweet corn, cotton, and cantaloupe. The crops were tomatoes in 1984, 1985, 1987, and 1990, cantaloupe in 1986, cotton in 1988, and sweet corn in 1989. The basic configuration of the SDI system, which did not change, will be described in the following sections. The individual experiments will be summarized after the system description.

The experimental design used to construct the field installation was a randomized block consisting of three treatments with four replications. This was modified in 1987 and the blocks were split into two sub-plots. Each main plot was 91 m long and contained 10 beds spaced 1.63 m from center to center. Installation of irrigation supply line, centrifugal pump, fertilizer injector (flow-sensing, proportioning pump) manifold, mainlines, and

Table 1
Applied water, marketable yields, soluble solids, and water use efficiency for tomatoes grown at California State University, Fresno in 1981

Treatment no.	Irrigation method	Irrigation control method	Marketable fruit[a] (Mg ha^{-1})	Non-marketable fruit[d] (Mg ha^{-1})	Total soluble solids[b] (Mg ha^{-1})	Total solids (Mg ha^{-1})	Applied water (mm)	WUE[c] (kg m^{-3})
1	Furrow	Open Evap Pan	89.67 d	15.69 e	4.76 c	5.53b	627	14.3
2	SDI	Open Evap Pan	132.26 a	38.11 a	5.24 ab	6.94 ab	648	20.4
3	SDI	Screened Evap Pan	116.57 abc	33.63 ab	5.47 b	5.79 b	610	19.1
4	SDI	Open Evap Pan (75%)	96.62 c	20.18 d	4.97 b	6.89 ab	488	19.8
5	SDI	Van Bavel E_t model	96.17 c	29.14 abcd	4.36 c	6.09 ab	620	15.5
6	SDI	Soil Sensor@15/30 cb	125.54 ab	31.38 abc	5.55 b	6.53 ab	1029	12.2
7	SDI	Soil Sensor@25/40 cb	112.09 abc	13.45 e	5.41b	6.19 ab	742	15.1
8	SDI	Soil Sensor@35/55 cb	121.05 abc	22.42 bcd	6.96a	7.9 a	546	22.2

[a] Marketable fruit = red fruit + 2% green fruit + limited use fruit.
[b] Total soluble solids = Soluble solids (°Brix)* marketable yields (Mg ha^{-1}).
[c] Water use efficiency = Marketable fruit divided by applied water.
[d] Non-marketable fruit = 98% green fruit + blossom end rot sun scald + small. Column means followed by the same letters are not significantly different at the 5% confidence level. (Duncan's test of separation of the means).
[e] After: Rose et al., 1982.

plot manifolds was completed in the Spring of 1984. Filtration consisted of nested screens with 180 mesh being the finest. The headworks of the irrigation system consisted of three sections, each with computer-lysimeter feedback control backed up by a time clock, electric valve, water meter, pressure regulator, and pressure gauge leading to 7.6 cm diameter polyvinyl chloride (PVC) mainlines. At each plot a 2.5 cm diameter PVC manifold (sub-main) was connected by a 5.1 cm diameter PVC riser assembly to the mainlines. The riser assembly and plot manifold was made portable for the surface microirrigation plots. The microirrigation laterals, consisting of in-line turbulent flow emitters with a flow rate of 4 L h^{-1} spaced 0.91 m apart, were connected to the plot manifolds. For the SDI plots, an end-of-line manifold connected the trickle laterals to a single riser for flushing. The SDI laterals were installed in the center of each bed at a depth of 0.45 m from the top of the bed. The laterals for the surface microirrigation treatments were installed after planting and removed prior to harvest each year.

A large weighing lysimeter was used in a feedback mode to schedule irrigations automatically in the SDI and surface microirrigation treatments after 1 mm of crop E_t had been measured by the lysimeter. An irrigation of 25 mm was applied to the low frequency surface microirrigation treatment after 25 mm of E_t was measured by the lysimeter. The lysimeter was irrigated by SDI and corresponded to the high frequency SDI treatment. Details of the lysimeter are available in Howell et al. (1985) and the lysimeter control system in Phene et al. (1985).

2.2.1.1. Tomatoes. Processing tomatoes (cv UC82B) were grown in 1984, 1985, 1987, and 1990 in a Panoche clay loam soil, (Typic Torriorthents). In 1984 and 1985, the treatments were arranged in a randomized block design; in 1987 and 1990 a randomized split plot design was used and in both cases, treatments were replicated four times. The main treatments were high frequency SDI; high frequency surface drip irrigation (HFSD); and low frequency surface drip irrigation (LFSD).

The beds were spaced 1.63 m apart from center to center, and the tomatoes were planted at a density of approximately 150 000 seeds ha^{-1}. Each year, a soil fumigant (Vapam, ICI Chemicals)[3] was applied through the surface and subsurface microirrigation systems at a rate of about 346 L ha^{-1} with one 25 mm irrigation about 25 days prior to planting in order to fumigate the soil and control weeds and pests. Yearly, N and P fertilizer (11–48–0) was applied at the rate of 112 kg ha^{-1} at planting, directly below the seeds.

In 1984, the remaining fertilizer, 150 kg ha^{-1} of N, (US 28, 28% N as urea and 8% as H_2SO_4) were applied in daily increments through the irrigation system from May 19 to June 28. Tomatoes were planted on March 7 and emerged March 22. In the field, starting 26 days before harvest, irrigation water was reduced every 7 days to 0.9, 0.8, 0.7, and 0.6 of the water applied to the lysimeter to improve the soluble solid content of the tomatoes. Manual tomato harvest was from July 26 to August 1 and machine harvest was August 2. Manual harvest each year consisted of harvesting all the tomatoes in 6.1 m long sections; separating all tomatoes into four categories: (1) large red, (2) large green, (3) small, and (4) culls (rotten, sunburned, cracked, etc); and weighing each category.

[3] Product names are given for the benefit of the reader and do not imply endorsement by USDA-ARS.

In 1985, the same pre-plant fertilization was used as in 1984 with the remaining N and P being applied daily through the drip irrigation system as 12-12-0 (US 12-12-0, urea and phosphoric acid) and 17-0-0 (Can 17, calcium ammonium nitrate). These solutions were diluted to the specified daily rates and injected with a flow-sensing proportioning pump. The N and P from US 12-12-0 were 68 kg ha^{-1} each as urea and phosphoric acid respectively, and Can 17 provided 192 kg ha^{-1} as calcium nitrate (65%) and ammonium nitrate (35%). Total amount of N and P applied through the microirrigation system was 272 and 92 kg ha^{-1}, respectively. Tomatoes were planted in two rows per bed on February 22 with emergence March 20. Sprinkler irrigation was used to germinate and establish the tomato crop. In the field, irrigation water was reduced gradually to one-half the amount applied to the lysimeter over a 24 day period before harvest. Manual harvest of the tomatoes was from July 31 to August 2 and machine harvest was August 5.

In 1987, fertilizers injected with each irrigation were potassium nitrate (KNO_3) and CAN 17. Both fertilizer types were used to manage N and K efficiently. Total N and K injected were 301 and 381 kg ha^{-1}, respectively. Phosphoric acid was injected almost continuously through the microirrigation system at a rate of 0 (P_0), 15 (P_1), and 30 (P_2) mg P per kg of water for a total of 0, 67, and 134 kg ha^{-1} P. Phosphorous, applied as H_3PO_4, served a dual purpose of supplying P to the plant and maintaining the irrigation system clean and free of roots. The tomatoes were planted on February 25, emerged on March 20 and manually harvested on August 3–6.

The main irrigation treatments in the 1990 study were the same as in 1987. The sub-treatments were nitrogen (N), nitrogen and phosphorus (N, P), and nitrogen, phosphorus, and potassium (N, P, K) added daily by injection in the irrigation water. Fertilizer N, P, and K were injected daily through the drip irrigation system starting on Day 115 for N and Day 131 for P and K. Fertilizers used were calcium-ammonium nitrate (CAN 17), phosphoric acid, and potassium nitrate. Fertilizer amounts applied were 448 kg ha^{-1} N for the N sub-treatments, 448 kg ha^{-1} N and 101 kg ha^{-1} P for the NP sub-treatments, and 591 kg ha^{-1} N, 101 kg ha^{-1} P, and 442 kg ha^{-1} K for the NPK sub-treatments. The NPK sub-treatments received additional N because potassium nitrate was used as the source of K. Tomatoes were planted DOY 78 at a density of approximately 125,000 plants ha^{-1}. Sprinkler irrigation was used on DOY 80–81 for germination. The SDI system was used for germination starting on DOY 93 because of the lack of rainfall and the availability of sprinkler irrigation. Irrigation treatments were begun on DOY 130.

2.2.1.2. Melons. Cantaloupes (var PMR 45) were planted in one row per bed on 14 May 1986, with a seeding rate of 2.2 kg ha^{-1}. After a full stand was achieved, the population was thinned to approximately three to five plants m^{-2}. Pre-plant fertilizer (11-48-0) was applied at planting about 7 cm below the seeds at a rate of 16 kg ha^{-1} N and 26 kg ha^{-1} P. Potassium nitrate was dissolved and injected with the microirrigation systems with total application equaling 100 kg ha^{-1} N and 280 K kg ha^{-1} K.

Sprinkler irrigation was used to germinate and establish the crop. In June, bees were placed along the edge of the experiment for pollination purposes. Irrigation was begun 26 days after emergence (DAE), was maintained through the harvest period, and was terminated on DAE 96.

Cantaloupes were manually sorted and graded to determine the number and types of non-marketable fruits. Generally, quality is correlated with large, round, well-netted firm melons showing high soluble solids content. Non-marketable yield was determined by counting undesirable fruit with ground spot, growth crack, softness, and sunburn, and rotten cantaloupes. Normally, labor cost, quantity, and price fluctuations on the cantaloupe market prevent growers from harvesting melons more than three times. The fruit was harvested manually every 3 days with a total of eight harvest from 6 August to 21 August. Each time, a row length of 18.75 m was harvested from three different beds (6.25 m each) chosen at random in each plot.

Melons were harvested at the 'full-slip' stage when a thin abscission crack encircled the stem attachment at the fruit and the melon was easily detached. Melons were sorted manually to remove non-marketable fruit and graded using five sizes designated as '23, 27, 36, 45, and 54' with a standard sizing template. These sizing numbers are the number of melons that can be packed three layers deep in a commercial crate of 37–40 kg gross weight. Two additional categories (12 and 18) were used because there were too many melons in the '23' category to fit a normal distribution. After the eighth harvest, green melons were counted in each treatment.

2.2.1.3. Sweet Corn. Hybrid sweet corn (*Zea mays* L. Cv. Supersweet Jubilee) was grown during 1989 in a randomized split plot design with four replications. Main treatments were SDI and surface drip with two irrigation frequencies (HFSD, LFSD). The sub-treatments were phosphorus fertilization levels 0 (P_0), 67 (P_1), and 134 (P_2) kg ha^{-1} P added by daily injection of phosphoric acid in the irrigation water. Corn was sown on DOY 128; average plant density was approximately 72,000 plants ha^{-1}. Sweet corn was harvested from two sections of each sub-treatment from DOY 209–212 (each section consisted of 2 rows per 6.1 m bed). Total above-ground matter was harvested on DOY 207 and consisted of a 3 m section of bed (both rows) which was further sub-divided into stalks, leaves, ears, and tassels. Dry matter harvests were made in two sub-sample locations in the three field replications.

Sprinkler irrigation (121 mm) for germination and emergence was applied intermittently from DOY 129 to 146. Drip irrigation was started on Day 153 and continued until Day 220, 8 days after hand harvest but just prior to mechanical harvest. Both irrigation treatments were irrigated automatically with 1 mm of water after 1 mm of crop evapotranspiration had been measured with the weighing lysimeter. From DOY 153 to 181 all treatments received about 100 mm of irrigation water in excess of crop E_t because of concern (1) that the bed alignment problem of the SDI treatments could disproportionately influence early growth in those treatments, (2) the soil profile was extremely dry following cotton grown in 1988, and (3) negligible winter rainfall had occurred.

Fertilizers N and K were injected daily through the drip irrigation system starting on DOY 156. Nitrogen and potassium fertilizers injected were potassium nitrate (KNO_3) and calcium-ammonium nitrate. The total application of N and K from KNO_3 was 96 and 268 kg ha^{-1}, respectively. Additionally, the calcium-ammonium nitrate provided 220 kg ha^{-1} N. Total amounts of N and K injected were 316 and 268 kg ha^{-1}.

2.2.2. Results

2.2.2.1. Tomato. The yields of large red tomatoes obtained in 1984–1985 are given in Table 2 while the yields for 1987–1990 are given in Table 3. The data in Table 2 indicate that the SDI treatment produced a significantly greater red tomato yield than either the HFSD or LFSD when only P was injected with the irrigation water. Maximum yields occurred with P fertilizer injected at a level of 67 kg ha^{-1} (P_1) (Table 3). The extremely high tomato yields were a result of the precise application of irrigation and fertilizer. Components of yield increase in the SDI treatment included somewhat larger fruit sizes (not statistically significant) and a greater percentage of marketable tomatoes than in the HFSD and LFSD treatments. Although different years and fertility treatments were involved, we concluded that P injection through the drip lines caused a greater response in the SDI than the other treatments. The rooting and uptake patterns of P (Phene et al., 1986a) were deeper in the SDI treatment than in either the HFSD or LFSD. The availability of residual soil P nearer the soil surface caused the SDI treatment to show P deficiency in the petiole very early when P was not injected through the SDI drip line (Phene et al., 1988a).

In 1990 the N fertilizer treatment had significantly fewer fruit per unit ground area, smaller fruit, and lower total and red fruit yields than NP and NPK for the three irrigation treatments. This was not related to plant population differences across treatments (data not shown). Phosphorus application levels in supplemental P treatments were different between the 1987 and 1990 experiments (67 and 134 kg ha^{-1} P in 1987 versus 101 kg ha^{-1} P in 1990). Despite these differences, fruit yields were consistent in showing a positive response to supplemental rates P fertilization of 101 kg ha^{-1} or lower.

2.2.2.2. Cantaloupe. Table 4 shows that the number of ground-spotted and rotten cantaloupes in the SDI treatment was significantly lower than in the HFSD and LFSD treatments. This quality advantage in the SDI treatment is due to a dry soil surface condition during the formation and maturation stages of the crop. Conversely, growth cracks were more prevalent in the SDI treatment, probably because of the greater availability of water in the immediate root zone during harvest which is not the case in furrow-irrigated fields.

Table 5 shows the number of marketable (MM), non-marketable (NMM), and green fruit for each harvest as a function of the irrigation treatment. At the beginning of the harvest (1–4) the number of non-marketable fruit is significantly lower in the SDI treatment than in the HFSD (Harvests 2, 3, 4) and in the LFSD (Harvests 1 and 2). On a total basis, the number of non-marketable cantaloupes in the SDI treatment is, respectively, 42 and 39% lower than in the HFSD and LFSD. The final yield data are not significantly different among treatments; there is a trend favoring earliness, larger melons and more uniform harvest in the SDI treatment, in particular with respect to the HFSD.

2.2.2.3. Sweet corn. Sweet corn marketable weight and number of ears for all treatments are shown in Tables 6 and 7. The marketable weight and number averaged about 95 and

Table 2
Irrigation efficiency ($E_i = (E_t + \mathrm{Lr})/(E_t + \mathrm{Dp} + \mathrm{RO} + \mathrm{L} + \mathrm{S})$)

Irrigation treatments	1984 (N-only)				1985 (N + P)				1987 (N + P + K)[a]			
	E_i	E_t (mm)	Yr (Mg ha^{-1})	WUE (kg m^{-3})	E_i	E_t (mm)	Yr (Mg ha^{-1})	WUE (kg m^{-3})	E_i	E_t (mm)	Yr (Mg ha^{-1})	WUE (kg m^{-3})
SDI	1.10	659	121a[b]	18a	0.97	751	168a	22a	1.07	708	220a	31a
HFSD	1.09	650	126a	19a	0.98	714	152b	20b	1.05	695	201b	29b
LFSD	1.18	690	114a	16b	0.96	724	130c	18c	1.10	709	187c	26c

E_t = crop evapotranspiration, Lr = leaching requirement, Dp = deep percolation, RO = runoff, L = leaks, S = splash, yield of large red tomatoes (Yr), water use efficiency (Yr/E_t = WUE) for tomatoes grown with microirrigation at WSFS, California (from Phene et al., 1992b).
[a] Nitrogen = N, Phosphorus = P, and Potassium = K.
[b] Column means followed by similar letters are not significantly different at the 95% confidence level, as determined by the Duncan test on separation of means.

Table 3
Water applied (irrigation and rainfall, I + R), crop evapotranspiration (Et), yield of large red tomatoes (Yr) and water use efficiency (Y) E_t = WUE) for tomatoes grown with three microirrigation treatments and different fertility treatments for nitrogen (N), phosphorus (P), and potassium (K) at the West Side Field Station, Five Points, CA

Irrigation treatments	1987						1990					
	I + R (mm)	E_t (mm)		Yr (Mg ha^{-1})		WUE (kg m^{-3})	I + R (mm)	E_t (mm)		Yr (Mg ha^{-1})		WUE (kg m^{-3})
			P_0	P_1	P_2	P_2			N	NP	NPK	NP
SDI	664	708	184c[a]	220a	215a	31a	820	895	142.5cd	182.2a	179.3a	20[b]
HFSD	665	695	177c	201ab	192b	29b	817	850	143.3c	155.2b	154.3bc	18
LFSD	643	709	170c	187bc	183c	26c	820	816	125.4d	157.7b	141.6cd	19

[a] Within each year the column and row means in the yield of red tomatoes followed by similar letters are not significantly different at the 95% confidence level, as determined by the Duncan Test on separation of means.
[b] Data not available for statistical comparison.

Table 4
Total number and percentages of total non-marketable yield as affected by microirrigation treatment for cantaloupes grown at the WSFS, Five Points, CA in 1986

Treatment	Non-marketable cantaloupes					
	Ground spots		Growth cracks		Rotten	
	Count	%	Count	%	Count	%
SDI	19a[a]	17.6	60a	55.5	29a	26.9
HFSD	79b	42.0	50ab	26.6	59b	31.4
LFSD	72b	41.6	41a	23.7	60b	34.7

[a] Column treatment followed by similar letters are not significantly different at the 95% confidence level as determined by the Duncan Test on separation of means.

Table 5
Number of marketable, non-marketable, and green fruit at each harvest for cantaloupe grown at the WSFS, Five Points, CA in 1986

Irrigation treatment		Pick number									Count non-ripe melons	Total crop
		1	2	3	4	5	6	7	8	Total		
SDI	NMM	39a	13a	12a	8a	4a	12a	11ab	9a	108a	301	881a
	MM	109a	116a	83ab	57ab	43a	24a	11a	29a	472a		
HFSD	NMM	53ab	29b	24b	24a	14a	9a	17a	18a	188b	275	879a
	MM	64b	85a	68a	67a	52a	32a	22ab	26a	416b		
LFSD	NMM	76b	31b	13a	13a	4a	15a	6b	15a	173b	240	872a
	MM	96ab	99a	98b	39b	58a	20a	23b	26a	459ab		

[a] NMM is non-marketable melons, MM is marketable melons.
[b] Column treatments followed by similar letters are not significantly different at the 95% confidence level as determined by the Duncan Test on the separation of means.

Table 6
Sweet corn yield from three irrigation and three phosphorus fertilization treatments (0 (P_0) 67 (P_1), 134 (P_2) kg P ha^{-1}) in 1989 at the West SFS

Marketable weight (Mg ha^{-1}) Fertilizer treatments				
Irrigation treatments	P_0	P_1	P_2	Means
SDI[a]	27.0	29.2	30.2	28.8a[b]
HFSD	31.3	29.6	29.4	30.1a
LFSD	27.3	29.4	29.2	28.6a
Means	28.5a	29.4a	29.6a	

[a] Irrigation by fertilizer interaction at $p < 0.5$.
[b] Column and row means followed by the same letters are not significantly different at the 95% confidence level as determined by the Duncan multiple range test.

Table 7
Sweet corn yield from three irrigation and three phosphorus fertilizer treatments (0 (P_0) 67 (P_1), 134 (P_2) kg P ha^{-1}) in 1989 at the WSFS

Irrigation treatment	Marketable number of ears (number ha^{-1})			
	Fertilizer treatments			Means
	P_0	P_1	P_2	
SDI[a]	80,325	78,509	82,141	80,325a[b]
HFSD	79,618	78,810	79,818	79,415ab
LFSD	75,479	76,085	75,479	75,681b
Means	78,474a	77,810a	79,146a	

[a] Analysis of variance *F*-value not significant at the 95% level.
[b] Column and row means followed by the same letters are not significantly different at the 95% confidence level as determined by the Duncan multiple range test.

85% of the total weight and number (data not shown), respectively, harvested from the yield sections. There were no significant differences in marketable weight between irrigation treatments or P-fertilizer levels (Table 6). The marketable number of ears (Table 7) showed that the SDI treatment averaged about 6% more ears than the LFSD treatment. However, the ear number increase in SDI did not result in a significant weight increase. HFSD was not significantly different from SDI or LFSD. There was no significant difference between the P-fertilizer levels for marketable number of ears. The marketable yield averaged across all irrigation and P-fertilizer treatments was 29 Mg ha^{-1}, 78,474 ears ha^{-1}, and 1635 cartons ha^{-1} containing 48 ears per case. These were all exceptional yields. Commercially produced sweet corn in the SJV averages 1000 cartons ha^{-1} and approximately 47,500 marketable ears ha^{-1} of #1 corn which has 15 cm of edible length on the cob (Anderson, 1998). The average yield across all treatments was 65% higher than the average for commercially grown sweet corn in California.

The distribution of roots was also studied under sweet corn as a function of drip placement and fertilization treatment (Phene et al., 1991). Root sampling at the end of the growing season indicated that: (1) Root extension continued in excess of 2 m in both the surface and SDI systems at all levels of P fertilization. (2) The greatest differences between surface and subsurface systems were observed in the top 45 cm depth. Higher root density was observed in the surface 30 cm in the surface-microirrigated plots while the sweet corn in the SDI plots had greater root length density than the surface microirrigated plots below 30 cm, and (3) the greater root length density in the subsurface irrigated sweet corn was not reflected in a similar increase in total above-ground dry matter.

2.2.2.4. Water use efficiency. Water use efficiency (WUE) has important implications when considering irrigation, soil and water conservation, productivity, and sustainability of irrigated agriculture. WUE is usually defined as the ratio of dry matter yield (*Y*) per unit of water evapotranspired, $(E + T)$ for a non-water stressed crop. Phene et al. (1988b) have shown significant increases in tomato yields with precise daily injections of

Table 8
Yearly values of reference and crop evapotranspiration, rainfall, irrigation, drainage, WUE for several crops irrigated by SDI from 1984 to 1990, at WSFS, CA

Crop (year)	E_{to} (mm)	Crop and soil E_t	Rainfall	Irrigation	Drainage	WUE[a] (kg $^{-3}$)
Tomato (1984)	1823	959	104	692	0	2.2
Tomato (1985)	1720	855	127	792	59	2.41
Cantaloupe (1986)	1701	863	167	552	90	1.81
Tomato (1987)	1657	793	187	658	36	3.88
Cotton (1988)	1583	979	205	694	83	3.13
Sweet corn (1989)	1514	693	86	667	2	2.92
Tomato (1990)	1618	875	145	773	38	2.41
Means (1984–1990)	1659	860	146	689	44	2.68

[a] WUE calculated as the total above-ground dry matter divided by the applied irrigation water.

nitrogen, phosphorus, and potassium designed to match the rates of crop uptake. These yields were achieved without any increase in E_t. SDI also improved WUE, since evaporation from the SDI systems was minimal, transpiration (T) increased and increasing T improved evaporative cooling of the crop canopy, increased stomatal opening, and photosynthesis (Phene et al., 1987).

The WUE for tomatoes in 1984, 1985, and 1987 is summarized in Table 2. In 1985, when N and P were injected and 1987, when N, P, and K were injected, all yields and WUE increased significantly over N alone but E_ts did not increase proportionally. The yield and WUE of the SDI tomato increased significantly over HFSD and LFSD. The WUE of the 1987 HFSD increased by 93% over that of the 1984 LFSD. These results suggest that nearly twice as many tomatoes could be grown with the same amount of water when SDI and precise fertigation are practised, compared to conventional irrigation practices or with inadequately fertilized microirrigation systems.

The irrigation efficiencies (Table 2) indicate that the field systems were operated at a slight deficit and probably without deep percolation. Eventually some extra water will need to be applied to leach salts to maintain a salt balance in the root zone. In shallow ground water conditions if the ground water level is lowered due to reduced deep percolation the salt balance can be maintained without increasing the drainage outflow in areas with subsurface drainage.

The WUE data of all the crops grown with the SDI system on the lysimeter at the WSFS are summarized in Table 8. The WUE was calculated by dividing the total above-ground dry matter yields by the volume of applied irrigation water. The E_t represents the full year E_t measured by the lysimeter and is 52% of the reference E_t. The change in soil water content in the lysimeter indicated that a yearly net 76 mm of water was taken from the soil profile during the 7-year period and 51 mm of water was drained below the 2.25 m depth, which is equivalent to a net leaching fraction of 0.06. Most of the drainage occurred in conjunction with precipitation following sprinkler irrigation for crop germination.

Part of the failure of the numbers to balance is attributed to breakdowns of the lysimeter during the 7-year period. These results demonstrate the potential of SDI for increasing WUE and minimizing deep percolation with an attendant reduction in potential pollution from nitrate and salts.

2.3. Brawley, California

2.3.1. Materials and methods

Research was conducted on the USDA-ARS Irrigated Desert Research Station near Brawley, in the Imperial Valley of California to test the use of SDI for the production of alfalfa (Hutmacher et al., 1992, 1996). The research plot was a 2.8 ha field with Holtville silty clay soil on which there were five irrigation treatments and three replications. The SDI system used lateral spacings of 1.02 and 2.04 m with the laterals being centered under the alfalfa bed. 2 l per hour pressure compensated drippers were installed on a 1.02 m spacing along the length of the lateral. The initial lateral installation was at a depth of 0.4 m. After 2 years of operation the original system was modified and a set of laterals was installed at a depth of 0.6 m and used for the remainder of the project. The original laterals were removed at this time. Trifluralin-impregnated emitters were used for the second installation. Yields were determined using commercial-type operations for harvest including swathing, raking, and baling. Each of the bales was weighed in the field because of problems with wet spots in the field.

Water supply was the Colorado River which had an EC of approximately 1.15 dS m^{-1}. Water was filtered with dual sand media filters and a 200 mesh screen filter. The filters were flushed automatically daily and manually once a week. The system was instrumented and monitored from the Water Management Research Laboratory in Fresno as well as on-site. A weighing lysimeter was used in a feedback mode to control irrigation of the microirrigation system and was set to apply 1 mm of irrigation after each 1 mm of E_t. The furrow plots were irrigated with gated pipe and received from 35 to 55 mm of water in each application. The total application was intended to be the same for each irrigation method.

2.3.2. Results

In 1991 the SDI system applied 1174 mm and the furrow irrigation system applied 1310 mm of water. Rainfall is insignificant in the Imperial Valley. In 1992 the SDI system applied 1108 mm and the furrow applied 1102 mm. The lower irrigation depth in the furrow was due to inadequate winter and spring irrigation. In 1991, the establishment year, the yield in the 2.04 m lateral spacing was 17% lower than the 1.04 m lateral spacing and the furrow plot yields were 33% lower than the 1.04 m lateral drip spacing. In 1992 the yield on the 2.04 m lateral spacing was 102% of the yield on the 1.04 m lateral spacing and the yield on the furrow plot was 14% less than that on the 1.04 m lateral spacing plots. The yield in 1992 for the 2.04 m lateral spacing in the SDI system was 10 Mg ha^{-1}. Water extraction was monitored to a depth of 2.4 m using neutron attenuation.

The initial installation of the drip lateral at a depth of 0.4 m was not adequate to prevent surface wetting which created problems during the harvest. When the system was installed at a depth of 0.7 m the surface wetting problem was eliminated and the system could be run even during harvest.

Results from the 94–95 studies demonstrated that the applied water and E_t were within 5% for both the drip and furrow plots but the yield in the SDI plots was approximately 26–35% higher than in the furrow plots. Soil water data indicated that most of the water use was in the upper meter of the soil profile. Increases in the WUE in this study were a result of improved yields not reduced water application. Soil salinity data for the drip plots indicated that a large irrigation would be required every 2–3 years for leaching and salinity control.

One advantage of the SDI system in alfalfa production was the ability to operate the system continuously even during harvest which reduced the stress on the plant and provided for faster regrowth. SDI also eliminated problems associated with damage to the crown of the plant immediately after harvest.

3. Field studies

3.1. Britz Farms

3.1.1. Materials and methods

In 1991 an SDI system was installed on five plots each 2.4 ha (60×396 m^2) in size on two adjacent fields (sections 1 and 36) located on Britz Farms on the west side of the SJV, approximately 10 km south of Mendota, CA. A different type of drip tubing was installed in each group of five plots. The tubing-types and characteristics are given in Table 9.

A lateral length of 198 m was used for the T-System, Chapin and Typhoon tubing while a lateral length of 396 m was used for the Roberts and Ram tubing. Lateral spacings of 2 and 1.7 m were used with a depth of installation of approximately 0.45 m. The 2 m spacing was equivalent to installing the tubing between every other row of cotton and the 1.7 m spacing corresponded to the tomato bed width at installation. The microirrigation system operation was controlled and monitored on-site and/or remotely from the Water Management Research Laboratory (WMRL) (Phene et al., 1992a) using a cellular phone interfaced to the logger/controller located on site. A micrologger/controller was used to control the irrigation valve opening and closing, to monitor the water level in an evaporation pan and to monitor flow and pressure in each treatment.

The furrow-irrigated field was set up for graded furrow irrigation with run lengths of 396 m on a 0.1–0.2% surface slope with no provision for tailwater recovery and re-use.

Table 9
Characteristics for drip tubing used at SDI plots on Britz Farms Shallow Ground Water Management Demonstration project

Tubing	Characteristics
Ram	0.03 l min^{-1} m^{-1}, 1 m emitter spacing, ID = 18 mm, 244 kPa
T-Systems	0.025 l min^{-1} m^{-1}, 0.3 m emitter spacing, 15 mil tubing, 105 kPa
Chapin	0.037 l min^{-1} m^{-1}, 0.3 m emitter spacing, 20 mil tubing, 105 kPa
Typhoon	0.025 l min^{-1} m^{-1}, 1 m emitter spacing, 20 mil tubing, 105 kPa
Roberts	0.025 l min^{-1} m^{-1}, 0.6 m emitter spacing, 10 mil tubing, 70 kPa

The water was delivered to the furrows by gated pipe from a Westlands Water District metered valve turnout.

Irrigation scheduling on the furrow-irrigated plots was the responsibility of the cooperator and scheduling of the microirrigation system was the responsibility of WMRL personnel. The automated evaporation pan located on-site was used to control the SDI system. Pan evaporation was multiplied by a pan factor (K_{pan}) and a crop coefficient (K_c) to calculate the crop evapotranspiration (E_{tc}). This calculation was made on an hourly basis and the E_{tc} was accumulated until 4 mm of water was used by the crop. Irrigation was applied a maximum of twice daily and any amount of E_{tc} accumulated in excess of 4 mm was carried forward to the next irrigation period. The pan coefficients and crop coefficients were developed from previous work by the WMRL. The modified crop coefficient used for cotton was

$$K_c = 7.12e^{-3} - 7.28e^{-4}(\mathrm{GDD}) + 3.4e^{-6}(\mathrm{GDD})^2 - 2.34e^{-9}(\mathrm{GDD})3 + 3.58e^{-13}(\mathrm{GDD})^4 \tag{1}$$

where GDD is growing degree days after emergence to a base of 13°C (Ayars and Hutmacher, 1994). This coefficient was derived for a water table depth of 2 m and a ground water salinity of 7 dS m^{-1}.

Cotton (var SJ-2 or MAXXA) was planted in section 1 on a 1 m row spacing in each of the 3 years of the project on one set of five plots. The planting dates were 20 April 1991, 13 April 1992, and 14 April 1993 with germination occurring approximately a week to 10 days later. The field was pre-plant irrigated using surface irrigation during the winter and the seed was planted in moist soil. Fertilization and cultural practices were the responsibility of the cooperator. Fertilization was designed to meet University of California guidelines for good cotton nutrition. Cotton yields were determined solely by machine harvest by measuring the area required to fill a harvest module and using the lint weight from that module and the harvested area to calculate the lint yield.

The lateral spacing of 1.7 m in the five plots in section 36 was determined by the tomato bed size which was in place at the time of installation. The tubing was plowed into the center of the bed at a depth of 0.45 m using a shank designed for this purpose. The rotation on this field was tomato, cotton, and tomato.

Processing tomato (var. Apex 1000) was planted on 1.7 m beds on 11 March 1991 and harvested on 8 August 1991. Two rows of tomatoes were planted on each bed and the drip lateral was centered between the rows. The next crop was cotton (var. Acala Maxxa) which was planted on beds with a 1 m spacing on 13 April 1992 and harvested on 19 October 1992. The third crop was processing tomato (var. Hunt 427) which was planted 7 March 1993 on 1.5 m wide beds. This crop was harvested 26 July 1993.

Yields were determined by both hand and machine harvest. The tomato yield was determined by a hand harvest procedure which consisted of stripping all fruit from the plants in a 6 m length of row and sorting by size and color and weighing each component. Machine harvest yields were done by determining the harvest area required to fill a set of tomato trailers and using the measured load weight to calculate the yield. Cotton yields were determined solely by machine harvest by measuring the area required to fill a module and using the lint weight from that module and the area to calculate a yield.

In 1993 as a result of poor stand establishment and plant growth in the tomatoes on section 36, an extensive soil sampling was done in the affected areas to determine if salt accumulation was affecting plant growth and development. The soil profile was sampled in 15 cm intervals to a depth of 0.6 m in a transect perpendicular to the drip lateral. The sample sites extended across a full repeating pattern starting with a lateral centered on the bed and ending with a lateral centered on a bed. The soils were dried, ground, and saturated using standard methods (USEPA, 1979). The saturation extract was analyzed for electrical conductivity, boron, chloride and nitrate.

Data were collected on both sections to describe the number of repairs required after the first season and the probable cause of damage. The damage was classified as cut, chewing, or dislocation. Cuts were generally caused by tillage equipment, chewing was caused by gophers, and dislocation was also by tillage equipment. The damaged areas were found by operating the system and looking for wet spots after which a hole was dug to the damaged area and a repair made. Repairs were generally completed at the beginning of each growing season.

3.1.2. Results

3.1.2.1. Water balance. The water balance data for cotton on section 1 of the Britz site for 1992 and 1993 are given in Tables 10 and 11, respectively. In Tables 10 and 11, the E_{tc} was estimated using total dry matter (TDM) (Davis, 1983). In 1992, the water applied by

Table 10
Water balance for cotton grown on the Britz Shallow Ground Water Management Demonstration Project (1992)

Irrigation system	Soil water depletion (mm)	Effective Rain (mm)	Applied water (mm)	Total dry matter (kg/ha)	Cotton E_{tc} TDM (mm)	Groundwater contribution (%)
Furrow	35	3	475	9738	437	−17
Roberts	−7	3	300	10250	456	35
Ram	−7	3	377	13790	577	35
Chapin	−7	3	380	13143	566	33
Typhoon	−7	3	378	14847	613	39
T-System	−7	3	390	14300	534	28

Table 11
Water balance for cotton grown on the Britz Shallow Ground Water Management Demonstration Project (1993)

Irrigation system	Seasonal		Soil water depletion (mm)	E_{tc} CIMIS (mm)	E_{tc} TDM (mm)	Groundwater contribution (%)
	Applied water (mm)	Effective rain (mm)				
Furrow	335	0.0	14	578	645	40
Roberts	211	0.0	17	578	593	61
Ram	340	0.0	23	578	823	37
Chapin	366	0.0	24	578	750	33
Typhoon	307	0.0	20	578	657	43
T-System	292	0.0	16	578	630	47

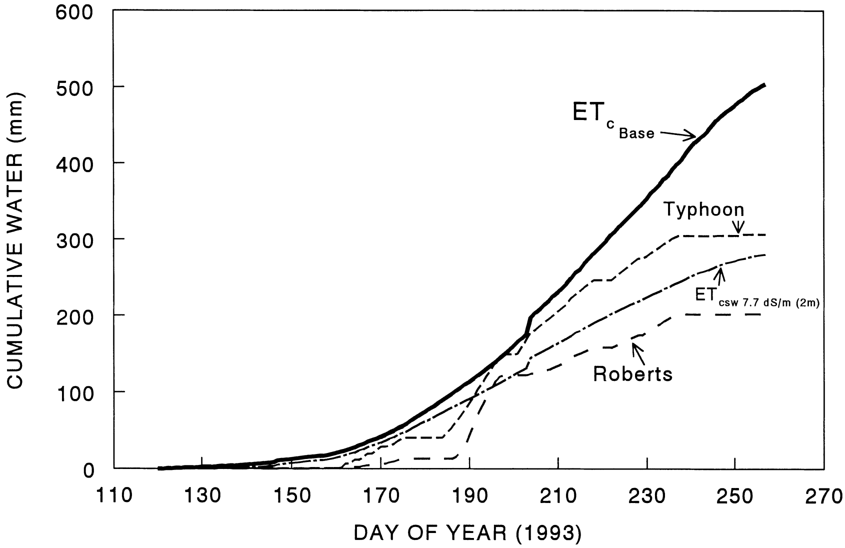

Fig. 1. Cumulative irrigation water applied and calculated evapotranspiration for cotton at Britz Shallow Ground Water Management Demonstration Project in 1993.

the furrow system was slightly greater than the crop E_{tc} and resulted in some deep percolation. In the drip plots high frequency irrigation coupled with modified crop coefficient resulted in less total applied water than the furrow-irrigated plots and in a ground water contribution to the crop water use. In 1993 both the drip and furrow-irrigated plots were under irrigation which resulted in substantial use of shallow ground water by the cotton crop.

Total applied water with the Roberts tubing was lower than with any of the other systems because of the system operation. The lower pressure requirements for the Roberts tubing were difficult to maintain and flow was periodically stopped by the pressure reducing valve which resulted in substantial under-irrigation. The Typhoon system nearly matched the water requirement during the irrigation season. The cumulative applied water for the Roberts and Typhoon system is plotted in Fig. 1 along with the accumulated E_{tc} calculated on the base crop coefficient and the accumulated E_{tc} based on the crop coefficient appropriate for a water table at a depth of 2 m with an electrical conductivity of 7 dS m^{-1}.

3.1.2.2. Yield (Section 1). The cotton yield data for each of the 3 years on section 1 is given in Table 12. The data show that the yields were improving in the drip-irrigated plots during the 3 years of the project. The average yields for the drip plots were 1390, 1780, and 2042 kg ha^{-1} in 1991, 1992, and 1993, respectively. The yields in the furrow-irrigated plot remained constant during this time. The cotton yields in the furrow-irrigated plots were typical of the previous production levels on this field.

The highest yield was obtained in 1993 on the plot receiving the smallest amount of irrigation water during the irrigation season. The furrow plot yield in 1993 was

Table 12
Yield of cotton grown using SDI on the Britz Shallow Ground Water Management Demonstration Project in 1991–1993

Irrigation system[a]	1991	1992	1993
	(Mg ha^{-1})	(Mg ha^{-1})	(Mg ha^{-1})
Roberts	1.4	1.6	2.3
Ram	1.3	1.7	1.9
Chapin	1.5	1.8	2.6
Typhoon	1.3	1.9	1.7
T-Systems	1.4	1.9	1.7
Furrow	1.5	1.4	1.5

[a] Product names are given for the benefit of the reader and do not imply endorsement by the USDA-ARS.

comparable to that of 1991 in a situation with apparent under-irrigation and significant contribution from the ground water.

3.1.2.3. Yield (Section 36). The hand-harvested tomato yields for 1991 and 1993 are given in Table 13. All tomatoes harvested including large and small green and red tomatoes are included in the total. The cotton yield is the machine-harvested value.

In 1993 the hand-harvested yields were taken from areas which were not affected by poor germination and growth. The machine yields were generally lower than the hand-harvested yield. The hand harvest was selected for comparison to be consistent across years. Also we do not have machine harvest on all plots in 1991. There was little difference in hand-harvested tomato yields between 1991 and 1993. These yields compare to hand-harvested yields of 109 (1991) and 103 Mg ha^{-1} (1993) from a furrow-irrigated area adjacent to the drip plots. The cotton yield data compare to yield in the range of 676–2177 kg ha^{-1} for furrow-irrigated plots.

Both the drip and furrow-irrigated plots are located in a field containing perched groundwater at a depth of 1.5 m with an electrical conductivity of 3–5 dS m^{-1}. This water was available to both crops during the season and might supplement the water provided by the microirrigation system and reduce the impact of poor lateral placement relative to the crop in 1992 and 1993. This was particularly true for cotton which is a tap-rooted crop and has been shown to use water extensively from shallow groundwater.

Table 13
Summary of hand-harvested tomato yield (1991, 1993) and machine-harvested cotton yield (1992) section 36 of Britz Shallow Ground Water Management Demonstration Project

System	1991 Tomato (Mg ha^{-1})	1992 Cotton (kg ha^{-1})	1993 Tomato (Mg ha^{-1})
Typhoon	131	1910	146
T-System	131	2100	125
Chapin	136	2160	136
Ram	127	2140	117
Roberts	125	2140	110

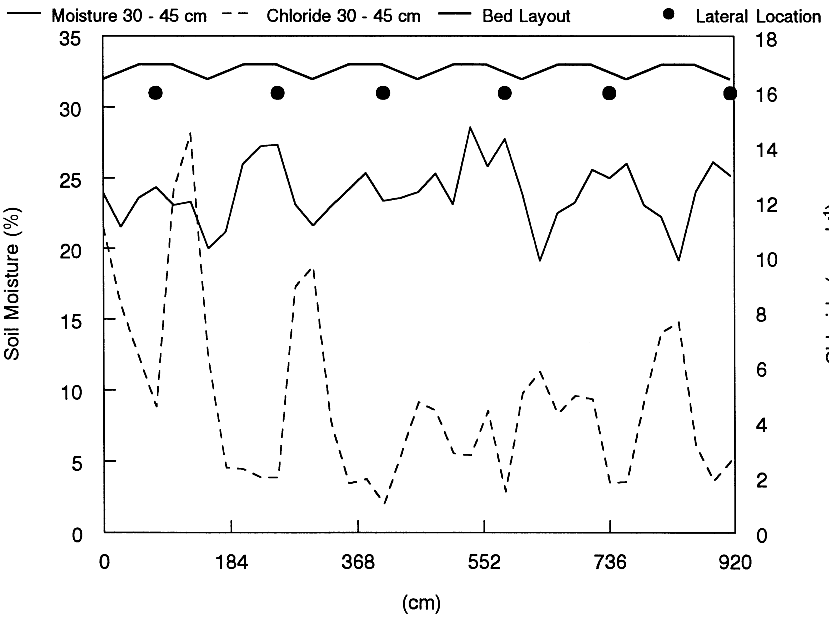

Fig. 2. Sub-surface drip irrigation lateral position relative to beds and resulting soil water and chloride distributions at 30–45 cm depth under tomato beds at Britz Shallow Ground Water Management Demonstration Project in 1993.

3.1.2.4. Soil water and chloride distribution. The position of the drip tubing relative to the bed placement in section 36 for 1991–1993 is shown in Fig. 2. In 1991 the drip lateral was centered on 1.67 m wide beds which were used as guides in the installation process. In 1992, the farmer opted to use a row spacing of 1 m for cotton which was not compatible with the existing lateral spacing. If the cotton was planted on approximately 0.76 m spacing the lateral would have been placed roughly between every other cotton row which was the desired configuration. In 1993 the tomato crop was grown in a 1.5 m wide bed.

In 1993 the placement of the laterals relative to the bed became critical since only a single row of tomatoes was planted on each bed and the best location for the lateral would be directly under the row. As seen in Fig. 2, after six beds the lateral was under the furrow and not under the bed. There was the potential when the lateral was under the furrow that salts in the soil water were transported under the row instead of away from the row.

The soil water data in Fig. 3 show the distribution in the top 0.45 m of the soil for the microirrigation system cross-section and for a comparable cross-section in furrow-irrigated plots. The data show that the top 0.15 m in the microirrigation system is drier than the comparable zone in the furrow system. There is also more separation between the next two depths in the microirrigation system than is found in the furrow system. Recall that the drip laterals were installed a depth of 0.45 m. There appeared to be a pattern of the highest soil water content being found under the drip laterals which means that it is not centered under the crop row by the end of the repeating pattern. Hanson and Bendixen

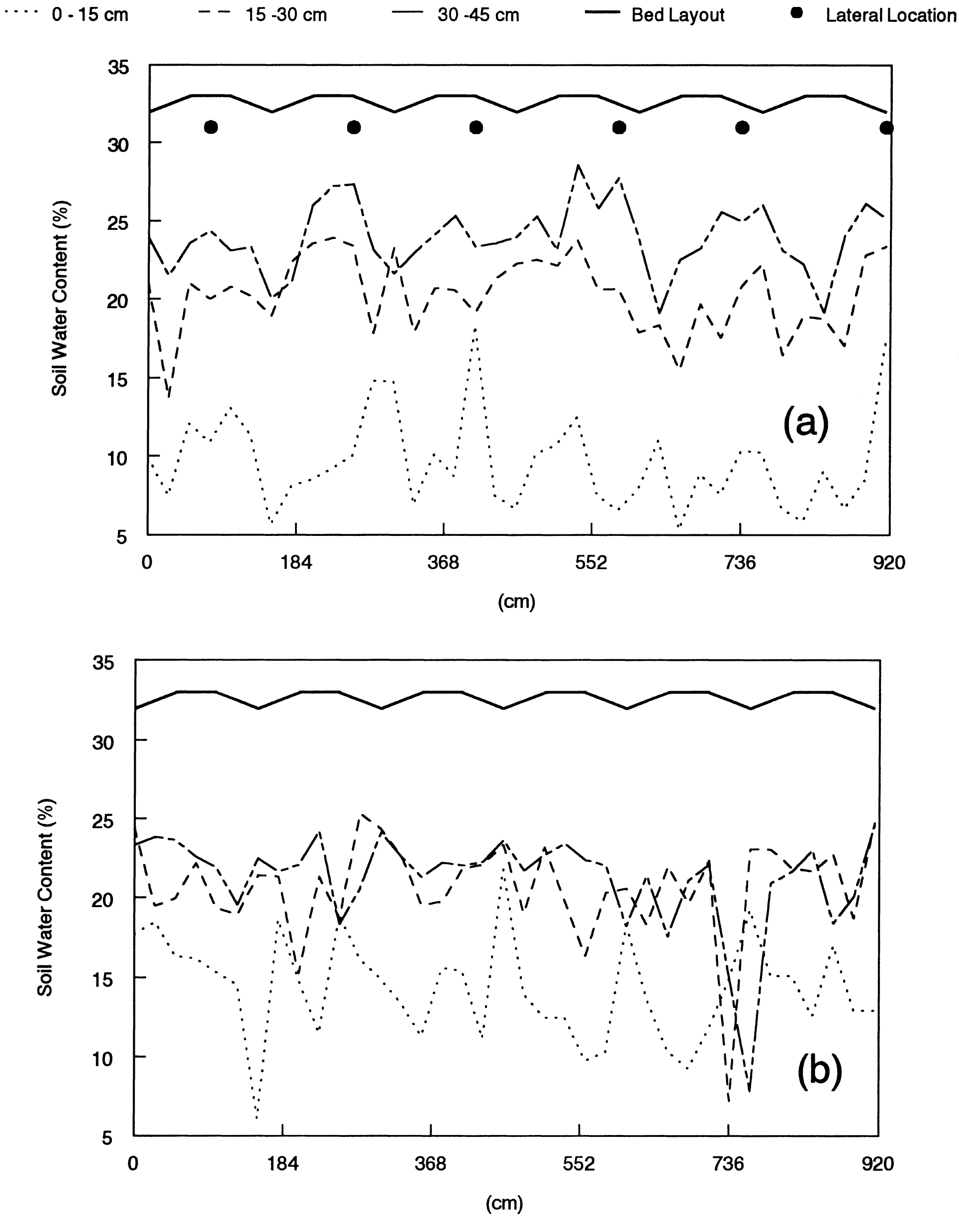

Fig. 3. Soil water content at depths of 0–15, 15–30, and 30–45 cm under (a) sub-surface drip irrigation and (b) furrow irrigation of tomato crop at Britz Shallow Ground Water Management Demonstration Project in 1993.

Table 14
Summary of damage and number of repairs to tubing in the SDI systems in 1992 and 1993 on the Britz Shallow Ground Water Management Demonstration Project

Damage	Typhoon		T-system		Chapin		Ram		Roberts	
	1992	1993	1992	1993	1992	1993	1992	1993	1992	1993
Cut	23	10	8	13	23	13	8	3	10	2
Chewing	16	16	8	14	8	7	3	2	19	12
Disloc.	4	6	1	8	5	0	2	0	4	2

(1995) found that the area around and below a drip tape installed at a depth of 0.13 m in both clay loam and fine sand was leached and salt accumulated away from the tape to the edge of a bed.

3.1.2.5. Physical damage. We observed that the laterals were subject to more damage when the lateral was not placed directly under the bed. The type of damage and the number of repairs are summarized in Table 14 for 1992–1993.

Much of the cutting and dislocation of the tubing was done on each end of a lateral where the tubing was not at a depth of 0.45 m. The tubing with the smallest wall thickness was subject to extensive damage by chewing and cutting. There were more cuts on tubes with the shorter laterals because the tube was brought to the surface mid-way in the field during installation to connect it to a sub-main. In areas where the tubing was not centered under the bed several hundred feet of tubing had to be re-installed in 1993 because it was brought to the surface during bed preparation. Some of the damage which is located at the end of the laterals can be minimized by changing the installation procedure but this is not the case when the bed configuration relative to the lateral is not correct. Steele et al. (1996) found extensive mechanical and rodent damage to drip tape installed at a depth of 0.28 m on a sandy loam soil. Chase (1985) found extensive damage to thin wall tubing installed at 0.08 m depth due to planting and weeding operations as well as fire ants and purple nutsedge rhizomes.

4. Uniformity studies

In irrigated agriculture, the preservation of water quality is dependent on the ability of the irrigation system to uniformly distribute water, chemicals, and fertilizers in time and space to the crop being grown. Drip irrigation and more specifically SDI systems can potentially achieve high application uniformity and can be operated to provide a high application efficiency (Phene et al., 1987). Evaluation of emitter discharge uniformity is necessary to determine if water and fertilizers are supplied to crops uniformly.

4.1. Materials and methods

The uniformity parameters chosen to evaluate microirrigation system application uniformity are: the Uniformity Coefficient (UC); the emitter flow variation (q_{var}); and the

Coefficient of Variation (CV) of emitter flow (Christiansen, 1942; Wu et al., 1979). The emitter flow variation is a measure of the variation of emitter discharge rate in a sub-main unit. These uniformity parameters are mainly affected by hydraulics (Wu et al., 1979), manufacturer variation (Bralts et al., 1981b) plugging (Bralts et al., 1981a, 1982), and temperature (Peng et al., 1984; Wu and Phene, 1984). The determination of UC, CV, and q_{var} can be obtained from field tests using an 18-point method (Bralts and Kesner, 1983; ASAE, 1989).

Field testing was done on five plots located in section 1 of the Britz experimental site after 2 years of operation and on plots at the WSFS which had been in operation for 9 years. All plots were randomly checked using the 18 points method described as follows. A tested unit consisted of an entire sub-main unit, which was divided into 18 sub-units, with an emitter being randomly selected in each of the 18 sub-units for testing. After leaks due to insect, gopher, and machine damage were repaired and the system was flushed thoroughly, the soil was excavated from around the emitter to be tested. The emitter discharge was carefully measured for 3 min at the required operating pressure and the flow rate was calculated by dividing the mean flow by the time of collection. The uniformity parameters were calculated individually for each plot using the 18 tested emitters.

4.2. Results

4.2.1. Britz system

The UCs of the five SDI fields in Section 1 at the Britz site were similar to measurements of UC, CV, and q_{var} made above ground before the tubing was installed. The UCs for the Typhoon and Ram systems were 96.97 and 95.47, respectively. The UCs for the remaining systems were 93.57 for the T-Tape, 76.34 for the Roberts, and 91.50 for the Chapin. The CV for these products after 2 years of use was 3.94 and 5.78% for the Typhoon and Ram, respectively, 9.11% for the T-Tape, 34.49% for the Roberts and 10.42% for the Chapin. The q_{var} for each of the products was 14.04 for the Typhoon, 18.69 for the Ram, 34.2 for T-Tape, 100 for Roberts, and 31.35 for the Chapin. It should be noted that the Roberts tape in use during this project was an experimental product made available for this project and is not commercially produced. The large CV and q_{var} of the Roberts product was a result of many leaks and pressure loss from damage to the tape from burrowing animals.

4.2.2. WSFS System

The experimental plots at the WSFS which had been in operation for 9 years were also tested using 18-point method. Three phosphoric acid sub-treatments (P_0, P_1, P_2) were tested using the procedures described in the previous section; in these sub-treatments, P_0, P_1, and P_2 refer, respectively, to no phosphoric acid injected, injecting phosphoric acid at 15 and 30 mg kg^{-1} P. The hypothesis was that phosphoric acid could prevent root intrusion and precipitation of chemicals.

Each sub-main unit tested consisted of three laterals, 91 m long (P_1 and P_2) or four laterals (P_0). The tested unit consisted of an entire sub-main unit which was divided into 18 sub-units with one emitter being randomly selected for testing in each sub-unit (random 18-point field test method). Leaks due to gopher or machine damage were repaired and the system was flushed thoroughly. In 1989 after 5 years of operation, nearly half of the drip laterals in the P_0 treatment were replaced due to root intrusion and/or plugging, and these laterals were excluded from this test. One emitter was located, operating pressure was set, the flow was measured for 3 min and the flow rate was calculated by dividing the mean flow by the time. The UC, CV, and q_{var} were calculated for each unit using the randomly selected emitters.

Results indicated that, except in Plot 11, sub-treatments P_0, P_1, and P_2 where 5% of the emitters in these plots were plugged, the UCs were above 95%, and the CVs were less than 5% and the q_{var} was between 10 and 25%. The cause of one emitter plugging in each sub-plot in Plot 11 could not be determined. These results demonstrate that the SDI systems performed very well after 9 years of operation. The injection of phosphoric acid may be helpful in controlling root intrusion and/or chemical precipitation since nearly half the laterals in the P_0 plots had to be replaced after 5 years of operation. However, from 1989 to 1992 there did not appear to be any significant difference in plugging between the rest of the original P_0 laterals and the P_1 and P_2 sub-treatments.

5. Discussion

Results from the studies presented in the previous sections address several areas of concern and provide partial answers to questions raised at the beginning of the manuscript. The depth of placement is one issue that still requires research but there are several findings which are relevant to the application of SDI without the complete answer being available for the depth of placement. In the research presented in the paper a depth of 45 cm was routinely used for the lateral depth placement and was very successful for several reasons. The soils in most of the installations were silty clay loam to clay loam soils which have the capability of moving water long distances from the drip emitter. In each case the SDI system was not used for germination of the crop. This was done with a second irrigation system, which is a practice that is quite common in SJV. Tomatoes are generally planted and irrigated with sprinklers for germination and after stand establishment furrow irrigation is used. Another practice which enables the use of SDI is pre-plant irrigation. Pre-plant irrigation is the application of water to a fallow field for purposes of leaching any accumulated salt and for refilling the root zone. In this situation cotton can be planted and germinated without any further irrigation. There is enough root development in the soil to permit the use of the SDI system when it is time to begin irrigation.

In sandy or 'lighter' soils the depth of installation has to be reduced to shorten the distance water has to move from the emitter to the root system. When the drip installation is not permanent the depth of installation tends to be very shallow <10 cm, which is common in irrigation of strawberries in California. Also, if the SDI system is going to be used for germination, then the depth of placement has to be reduced to minimize the distance to the surface and thus reduce deep percolation losses.

A depth of installation of 0.3 m has been used by Howell et al. (1997) and Lamm et al. (1995) in the production of corn on clay loam and loam soils. Camp et al. (1997) used a

0.3 m depth of placement for supplemental irrigation of cotton grown in the southeastern United States. Based on the results from a pot study, Plaut et al. (1996) recommended an installation depth from 0.4 to 0.5 m for cotton. Their results indicated that cotton roots would grow through dry soil to moisture at deeper depths.

Bed placement in relation to the drip tube is a critical consideration. Placement of drip laterals between every other row of cotton and centered between tomato and corn rows proved to be very effective and minimized the cost of installation. However, this dictates the row spacing for all succeeding crops. Lateral spacing has to be a multiple of the row spacing which will be used. When this was not followed for the tomato crop at the Britz site there was significant damage done to the microirrigation system, and adverse impacts on the yield. Alternate row spacing for lateral placement has been used by Howell et al. (1997) and Lamm et al. (1995) in the production of corn without any adverse impacts on yield. Camp et al. (1997) used alternate row spacing successfully with cotton. Tollefson (1985) reported on the Arizona System which installed drip tape at a depth of 0.25 m under every row of cotton on a 1 m spacing. This system was effective in meeting the peak E_t demands of cotton and in pushing salt to the edge of the bed.

The useful life of the system is a critical issue as is the uniformity of the system after a period of time. The uniformity results at the Britz site demonstrated that both hard hoses and tapes were suitable for use in SDI systems and that uniformity was good with either type of product. After 10 years of use at the WSFS the drip tubing was in excellent condition with good uniformity with the exception of one plot which had not been routinely irrigated with water containing phosphoric acid. Anecdotal evidence from the WSFS studies is that continuous injection of phosphoric acid at a concentration of $15\ mg\ l^{-1}$ is adequate for prevention of root intrusion. Howell et al. (1997) have successfully used phosphoric acid at a concentration of $13\ mg\ l^{-1}$ to prevent root intrusion. New drip products with Trifluralin impregnated emitters also have the potential to prevent root intrusion. One area of concern was the physical damage done to the tubing by rodents. This was more extensive in the tape products than the hard hose products.

Improvement in yield is one of the most touted reasons for switching to drip as is reduction in applied water. Dramatic increases were found in yields of tomatoes, corn, and cantaloupes. Some improvements were found in the yield of cotton. The maximum increases were a result of both improved water management and improved fertilizer management which was possible with a microirrigation system and with high frequency irrigation. WUE of individual crops was improved as a result of increased yield without increased water application. Any reductions in applied water were a result of switching from inefficient irrigation systems or management of the SDI system so that the crop used an alternative water source such as shallow ground water. Lamm et al. (1995) found that SDI reduced the non-beneficial use of water and maintained corn yield with 20% less applied water. Howell et al. (1997) did not measure significant yield increases with SDI provided adequate water was available in the soil profile from pre-plant irrigation and rainfall. Camp et al. (1997) found that cotton yields increased in 2 of 4 years in a humid area.

The issue of irrigation frequency is one that has not been fully resolved. The plots at the WSFS were irrigated up to eight times per day when controlled by a weighing lysimeter, while the plots at the Britz site were irrigated up to twice a day during the peak

E_t demand period based on pan evaporation and a crop coefficient. There is an interaction between the soil-type and the irrigation frequency which needs to be further studied to determine the movement of water away from the emitter. If excessive water is applied during an irrigation event using SDI there is the potential for deep percolation losses particularly if the soil is sandy. Caldwell et al. (1994) found that the highest irrigation WUE on subsurface drip-irrigated corn occurred as the irrigation interval was extended from 1 to 7 days. This also resulted in reduced deep percolation losses. They attributed this response in part to the use of rainfall by the crop. Crop yield WUE was not affected by irrigation frequency, which was also the case for Howell et al. (1997).

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